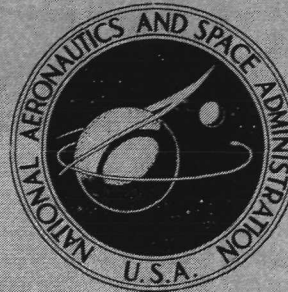


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**REVIEW OF DEFORMATION BEHAVIOR
OF TUNGSTEN AT TEMPERATURES
LESS THAN 0.2 ABSOLUTE
MELTING TEMPERATURE**

by Joseph R. Stephens

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Cleveland, Ohio 44135

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REVIEW OF DEFORMATION BEHAVIOR OF TUNGSTEN AT TEMPERATURES LESS THAN 0.2 ABSOLUTE MELTING TEMPERATURE

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SUMMARY

The deformation behavior of tungsten at temperatures less than two-tenths of the absolute melting temperature ($<0.2 T_m$) is reviewed, with primary emphasis on the temperature dependence of the yield stress and the ductile-brittle transition temperature. Work reported in the literature has been divided into extrinsic factors such as temperature, surface condition, etc., and intrinsic factors such as crystal orientation.

It is concluded that a model based on the high Peierls stress of tungsten best accounts for the observed mechanical behavior at low temperatures. Recent research suggests an important role of electron concentration and bonding on the mechanical behavior of tungsten. Future research on tungsten should include studies to define more clearly the correlation between electron concentration and mechanical behavior of tungsten alloys and other transition metal alloys.

INTRODUCTION

Tungsten, because of its high melting point (3685 K) and excellent strength-weight ratio at temperatures above 1700 K, has found increasing application since 1957 due to the requirements of the space age. Prior to this time, tungsten was used primarily as filaments in lamps, components in electronic tubes, and as welding electrodes. Currently, tungsten is being used in such varied applications as rocket nozzles, ionization surfaces for electrical propulsion in space, emitter surfaces for thermionic diodes, cladding for fuel elements for nuclear power generation in space, and miscellaneous applications such as radiation shielding for high-temperature furnaces and as thermocouples (refs. 1 and 2).

As tungsten and its alloys became more important as high-temperature structural materials, the low-temperature (i.e., $<0.2 T_m$, where T_m denotes absolute melting

temperature) mechanical properties came into focus primarily because of the relatively high ductile-brittle transition temperature of tungsten, normally well above room temperature for bulk material. Accompanying the lack of ductility near room temperature is the sharp increase in yield stress with decreasing test temperature which is peculiar to body-centered cubic (bcc) metals. It has been proposed in reference 3 that the high yield stress of tungsten at $<0.2 T_m$ leads to brittle failure since the fracture stress remains relatively constant with decreasing temperature; that is, when the yield stress σ_Y exceeds the fracture stress σ_F , brittle failure occurs. Further research has shown the situation to be much more complex.

The purpose of this report is to review the research that has been reported on factors governing the deformation of tungsten at $<0.2 T_m$, with primary emphasis on the ductile-brittle transition temperature. For the purpose of this report, the research reported in the literature has been divided into extrinsic factors (which include temperature, pressure, surface conditions, strain rate, grain size, and impurities) and intrinsic factors which include crystal structure, stacking fault energy, twinning stress, and dislocation mobility). A section of the report is devoted to alloying to reduce the ductile-brittle transition temperature; and, finally, a brief discussion of promising areas of future work is included.

EXTRINSIC FACTORS

Initial work on the deformation behavior of tungsten was mainly concerned with such extrinsic factors as temperature dependence of yield stress, effect of strain rate, surface condition, and so forth. The primary emphasis of these studies was to improve and, if possible, explain the relatively high ductile-brittle transition temperature (DBTT) of tungsten. Some of the more interesting results are reviewed.

Temperature

The effect of temperature on the yield stress of tungsten is shown in figure 1, which is based on the early work of Bechtold and Shewmon (ref. 3). The material used for this study was produced by powder-metallurgy techniques and had a recrystallized grain size of approximately 0.029-millimeter diameter. Characteristic of the bcc metals is the sharp increase in yield stress σ_Y with decreasing test temperature. Accompanying the increase in σ_Y is the reduction of ductility, shown in figure 1, which gives rise to the sharp DBTT of the bcc metals. Bechtold and Shewmon also showed that the brittle fracture stress σ_F is independent of temperature below the DBTT. Failure

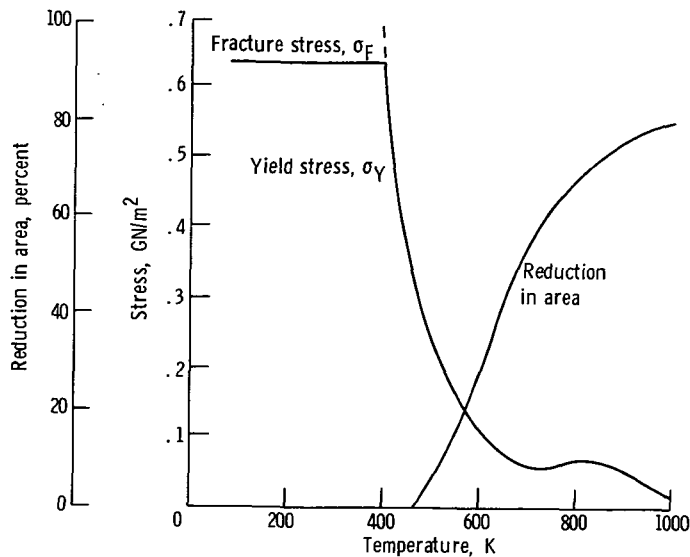


Figure 1. - Effect of temperature on flow and fracture characteristics of tungsten. Powder-metallurgy tungsten (200 ppm C; 80 ppm N). (From ref. 3.)

occurred by intercrystalline fracture, probably because of the high concentration of interstitial impurities in specimens used for this investigation.

In a more recent study, Wronski and Fourdeux (ref. 4) have determined the temperature dependence of the yield stress and brittle fracture stress of polycrystalline tungsten prepared from single-crystal ingots that were swaged to rod. Results of their study are shown in figure 2(a). Again a sharp increase in σ_Y with decreasing test temperature is observed; but, in contrast to the previous study, σ_F also increases sharply with decreasing temperature. Examination of fracture surfaces by microfractography techniques showed the fractures to be mixed grain-boundary cleavage type.

For comparison, the yield and fracture stresses for arc-melted tungsten are shown in figure 2(b) from a study by Raffo (ref. 5). It is evident from this work that the yield stresses in tension σ_{YT} and in compression σ_{YC} , as well as the brittle fracture stress σ_F , all fall on a continuous curve over the temperature range investigated. Also the yield stress increased rapidly as test temperature decreased. These observations indicate that brittle fracture occurs in tungsten at stress levels consistent with the level for macroscopic yielding. Similar results have been documented in the literature for steels (ref. 6) and for molybdenum (ref. 7).

Examination of fracture surface replicas in the electron microscope (ref. 5) confirmed that fracture was primarily by cleavage, with no more than 20 percent of the fracture surface containing intergranular fracture, in agreement with the observations of Wronski and Fourdeux (ref. 4).

Hull, Beardmore, and Valentine (refs. 8 and 9) have studied the deformation behavior of single-crystal and polycrystalline tungsten containing intentionally induced

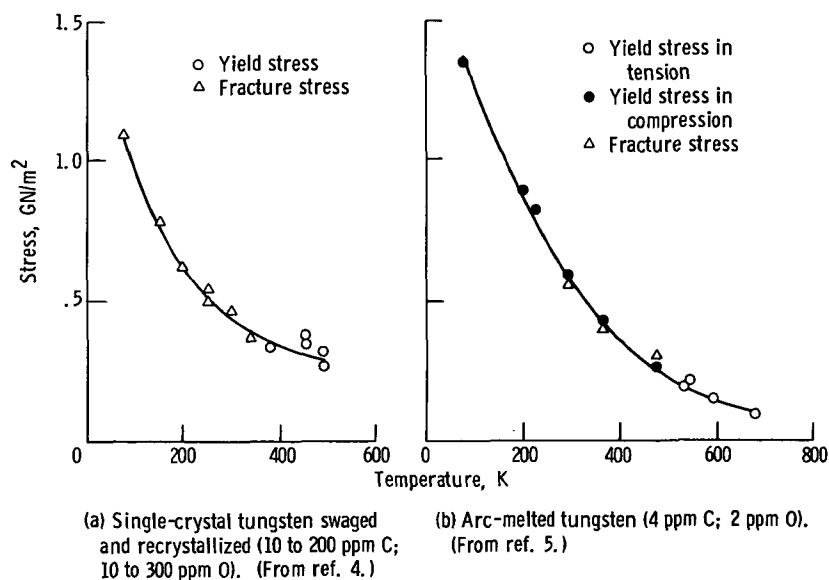


Figure 2. - Variation of yield stress and fracture stress for melted tungsten.

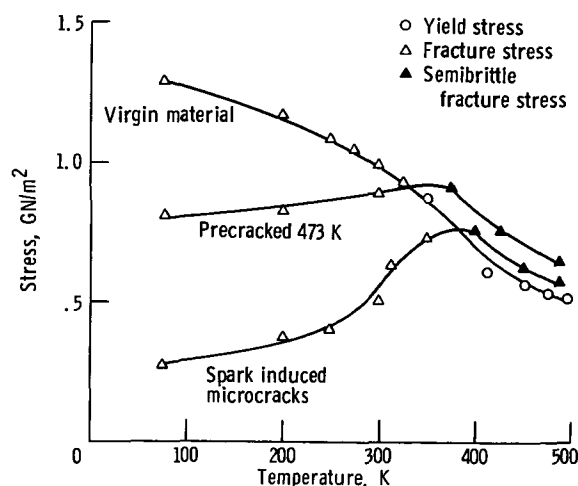


Figure 3. - Effect of temperature and intentionally induced microcracks on the deformation behavior of tungsten. (From refs. 8 and 9.)

microcracks. Figure 3 shows some of the results of their studies. For smooth polycrystalline tungsten, the characteristic increase in yield stress with decrease in test temperature was observed. The brittle fracture stress increases rapidly with decreasing temperature, falling on a continuous curve with the yield stress data in a manner quite similar to the results obtained by Raffo (ref. 5).

In contrast, figure 3 also shows that, when microcracks were present, the brittle fracture stress σ_F was essentially independent of temperature below the DBTT for specimens precracked by 2 percent prior to deformation at 473 K. Microcracks induced

by spark machining resulted in the brittle fracture stress decreasing with decreasing temperature. Above the DBTT, the yield stress σ_Y and the semibrittle fracture stress σ_{SF} increased with decreasing temperature in the normal manner. Brittle fracture was primarily by cleavage in both uncracked and cracked specimens. The difference in behavior of σ_F for the two types of induced cracks was postulated by the authors to be due to the relative sharpness of the cracks. Cracks produced by spark machining are sharp, and upon subsequent testing σ_F increases with increasing test temperature due to blunting of the crack tip by plastic flow. In the case of the surface cracks produced by prestraining at a higher temperature, blunting occurs during this prestrain, so that σ_F is independent of temperature upon subsequent testing.

In summary, the effect of temperature on the yield and fracture stress of tungsten is probably best represented by figure 2 (refs. 4 and 5). The yield stress σ_Y and the brittle fracture stress σ_F both lie along the same curve, increasing rapidly with decreasing test temperature. The presence of interstitial impurities segregated at grain boundaries or microcracks can drastically alter the temperature dependence of σ_F . The brittle fracture stress is then reduced from what is normally observed for high-purity, sound specimens. Since the brittle fracture stress is dependent upon a crack initiation term σ_{FI} and a crack propagation term σ_{FP} such that $\sigma_F = \sigma_{FI} + \sigma_{FP}$, it appears that interstitials segregated at grain boundaries provide an easy path for crack propagation, as shown by the intercrystalline failure (ref. 3) and hence lower σ_{FP} in figure 1. The introduction of surface microcracks provides crack sites for subsequent tests and lowers σ_{FI} , leading to premature failure.

Pressure

The general effect of a superimposed hydrostatic pressure is to increase substantially the ductility of otherwise normally brittle materials. Bridgman (ref. 10) showed, for a number of materials tested under uniaxial loading at pressure, that ductility was increased. The effect of pressure on the ductility of tungsten is quite similar to the effect of temperature in that a pressure-dependent ductile-brittle transition exists. Das and Radcliffe (ref. 11) have recently summarized the data for the pressure dependence of the ductility of tungsten, as illustrated in figure 4. These results are for powder-metallurgy tungsten that had been fabricated to rod and recrystallized prior to testing. Although there was considerable scatter in the data, probably because of the difference in purity of the tungsten used by each investigator, a pressure of 0.8 to 1.2 giganewtons per square meter (8 to 12 kilobars) is necessary for an increase in the ductility of tungsten at room temperature.

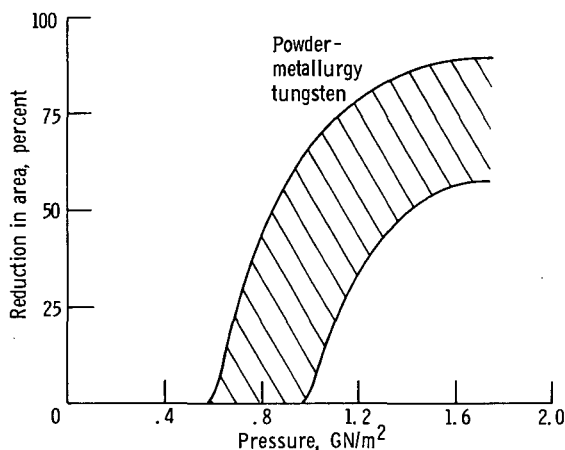


Figure 4. - Effect of pressure on the ductility of tungsten at room temperature. (From ref. 11.)

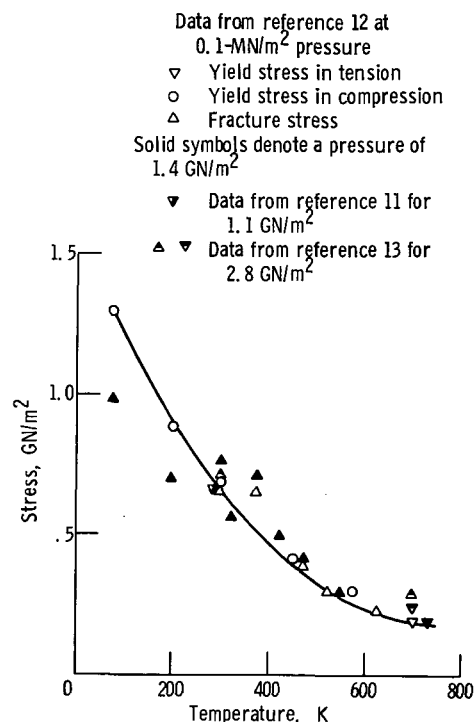


Figure 5. - Variation of yield stress and fracture stress with temperature for tungsten tested under pressure ranging from 0.1 MN/m² to 2.8 GN/m².

The effects of pressure on the yield stress and brittle fracture stress of tungsten have been determined by several investigators (refs. 11 to 13). Figure 5 summarizes the results for arc-cast tungsten tested in tension and compression at pressures of 1.4 and 2.8 giganewtons per square meter (14 to 28 kilobars) plus one data point for powder-metallurgy tungsten tested in tension at 1.1 giganewtons per square meter (11 kilobars) (ref. 11). The results show that σ_Y and σ_F are unaffected by hydrostatic pressures up to 2.8 giganewtons per square meter (28 kilobars) in that the sharp temperature dependence of both yield and fracture stresses exists over the temperature range investigated. Pressure thus has no apparent effect on these stresses at any of the temperatures investigated.

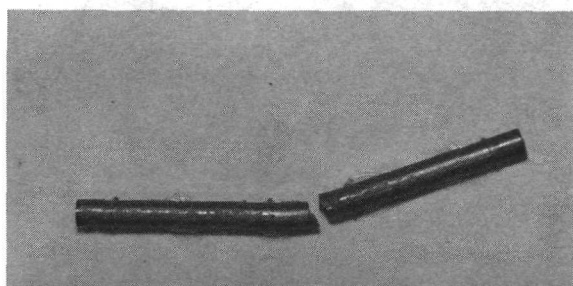
Further studies by Das and Radcliffe (ref. 14) have shown by transmission electron microscopy that no new dislocations were developed in tungsten at pressures up to 2.5 giganewtons per square meter (25 kilobars). New dislocations were observed in tungsten containing ThO_2 and HfC particles following pressurization to some 4.0 giganewtons per square meter (40 kilobars). It was further shown that the induced pressure promoted nucleation of new dislocations around precipitate particles of the proper size rather than multiplication of preexisting dislocations.

In summary, pressurization of tungsten up to 4.0 giganewtons per square meter (40 kilobars) fails to produce any irreversible changes in the yield stress of polycrys-

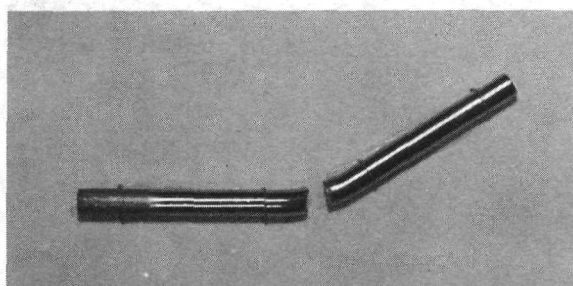
talline tungsten of good purity. Only when second-phase particles are present are dislocations produced during pressurization. Yield stress and brittle fracture stress fall on a continuous curve with temperature that increases rapidly with decreasing temperature in a manner quite similar for specimens tested under ambient pressure up to at least 2.8 giganewtons per square meter (28 kilobars).

Surface Condition

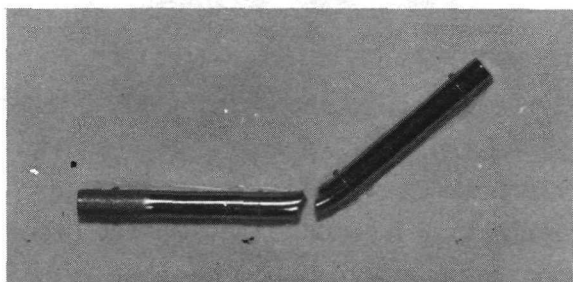
The surface condition of tungsten can play an important role in the deformation behavior at $<0.2 T_m$. The effect of surface roughness on the room-temperature ductility of tungsten was first investigated by Sedlatschek and Thomas (ref. 15). These investigators reported that the transverse rupture stress and bend ductility of wrought tungsten were improved by electropolishing the surface. In a series of studies, the author (refs. 16 to 19) further characterized the role of surface condition on the ductility of wrought tungsten and the DBTT and strength of recrystallized tungsten. Figure 6 illustrates the improvement in room-temperature ($T = 0.08 T_m$) bend ductility of wrought tungsten as a result of electropolishing the surface. The beneficial effects of electropolishing were attributed to removal of surface notches and cracks resulting



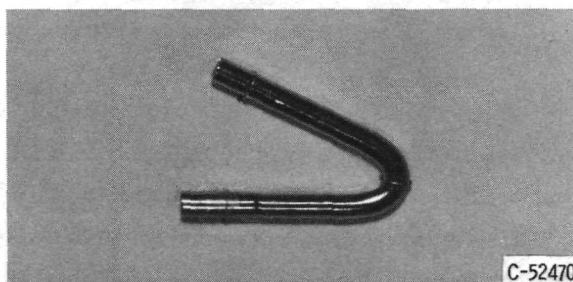
(a) As-received surface. Bend angle, 17°.



(b) Electropolished 0.00254 centimeter. Bend angle, 30°.



(c) Electropolished 0.00762 centimeter. Bend angle, 38°.

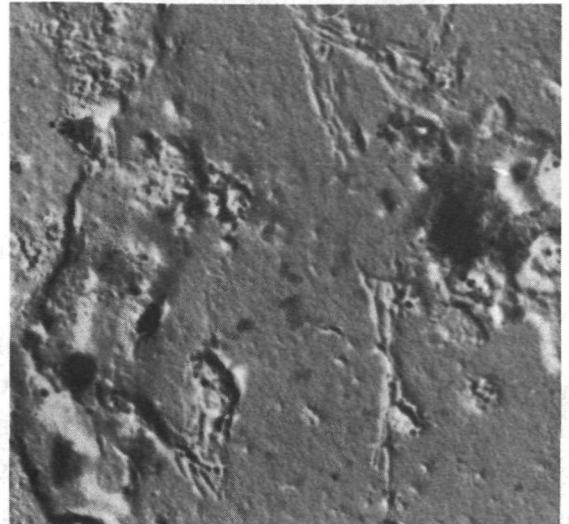


(d) Electropolished 0.0127 centimeter. Bend angle, 153°.

Figure 6. - Effect of surface removal by electropolishing on room-temperature bend ductility of tungsten. (From ref. 16.)



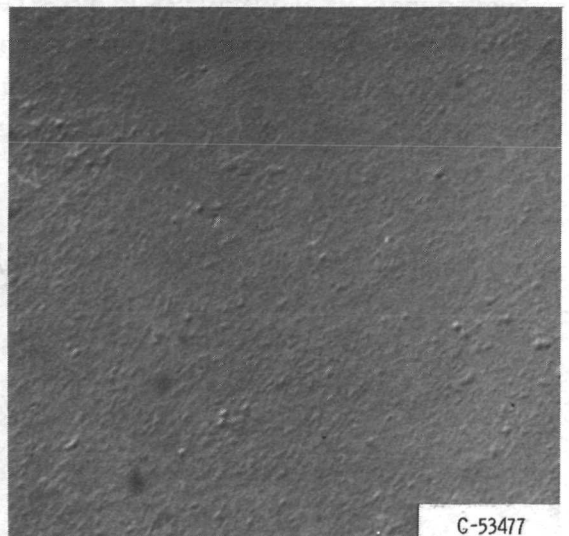
(a) As-received (swaged and cleaned).



(b) Diameter reduction, 0.00254 centimeter by electropolishing.



(c) Diameter reduction, 0.00762 centimeter by electropolishing.



(d) Diameter reduction, 0.0127 centimeter by electropolishing.

Figure 7. - Electron micrographs of as-received and electropolished surfaces. X20 000. (From ref. 16.)

from processing. Evidence for improved surface condition is shown in figure 7, where electron micrographs of replicas taken of the surface of the as-received rod and after removal of various amounts of material by electropolishing are shown.

An alternate explanation was proposed by Berghezan (ref. 20), who showed that heating wrought tungsten in air at temperatures ranging from 970 to 1470 K improved the room-temperature ductility. It was postulated that removal of a carbon-contaminated surface layer resulting from processing was responsible for the improved ductility.

It was subsequently shown by the author (ref. 19) and by others (ref. 21) that heating tungsten with a ground surface, and hence without a contaminated surface layer, in air led to improved room-temperature bend ductility and lowered the DBTT of recrystallized tungsten tested in tension. It appears probable that the beneficial results obtained (refs. 19 to 21) can be attributed to removal of surface notches by oxidation.

Effects of various surface conditions on the DBTT of tungsten are shown in figure 8. Either electropolishing or oxidizing, which leave the surface free of any detectable notches, produce the lowest DBTT of the various surfaces investigated. Roughening the surface by etching, mechanical working (sanding with emery paper), or introducing a controlled notch all raise the DBTT. As shown in figure 9, the ultimate tensile stress of specimens having a notch-free surface increased with decreasing temperature in a manner similar to the increase in σ_Y shown previously. Specimens with surfaces containing notches or cracks resulting from peening, grinding, etching, or introducing a controlled notch exhibited either a decrease in stress with decreasing temperature or an ultimate tensile stress independent of temperature in the brittle and transition zones in figure 9.

In summary, small surface defects can lead to premature failure of tungsten. Removing these defects by electropolishing (or by oxidizing) permits a more meaningful determination of the strength of tungsten to be measured; and the characteristic increase in stress with decrease in test temperature is observed.

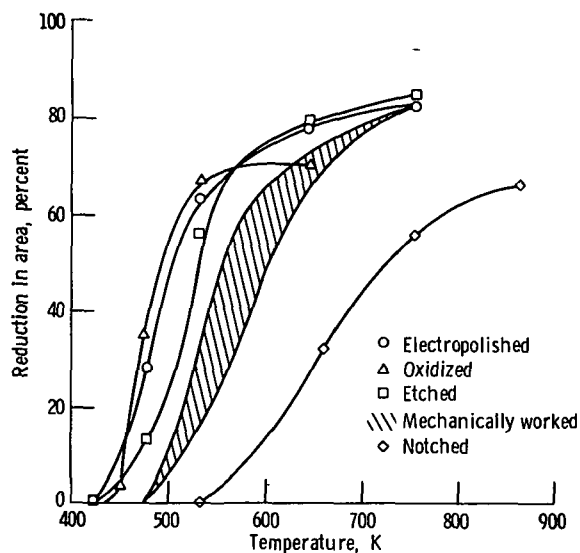


Figure 8. - Effect of surface condition on ductile-brittle transition temperature of tungsten. (From ref. 17.)

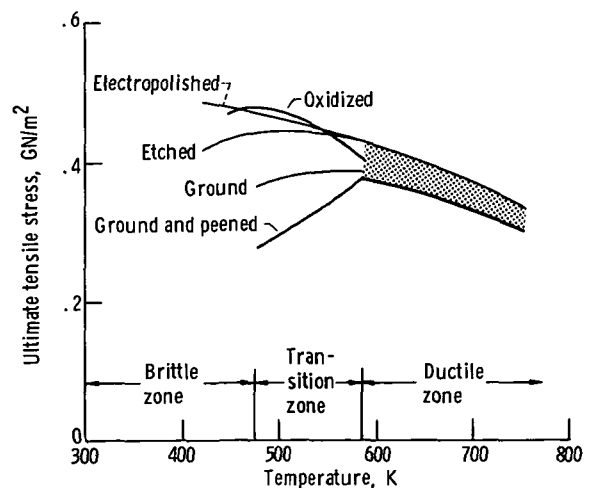


Figure 9. - Effect of surface condition on ultimate tensile stress of tungsten. (From ref. 17.)

Strain Rate

The early work of Bechtold (ref. 22) depicts in a quantitative manner the effect of strain rate on the yield stress of tungsten. At 525 K the variation of yield stress with strain rate obeyed the relation

$$\ln \sigma_Y = \tau \ln \dot{\epsilon}$$

where τ is the strain rate exponent and $\dot{\epsilon}$ is the applied strain rate. Figure 10 shows the effect of strain rate on σ_Y of tungsten where a value for τ of 0.15 was determined. The effect of strain rate on the tensile properties of tungsten is much greater than that observed for the more common metals such as copper, aluminum, or iron ($\tau_W \approx 12 \tau_{Fe}$) and points out the importance of controlling strain rate during testing of tungsten.

The effect of strain rate on the DBTT of tungsten was investigated by Chilton and Wronski (ref. 23). Figure 11 shows the effect of strain rate $\dot{\epsilon}$ on the ductile-brittle transition temperature T_T from their work, where a relation of the form

$$\exp(-\dot{\epsilon}^{0.09}) = K (E_0 - 0.3 T_T)$$

was obeyed. K and E_0 are constants over the range of experimental conditions investigated.

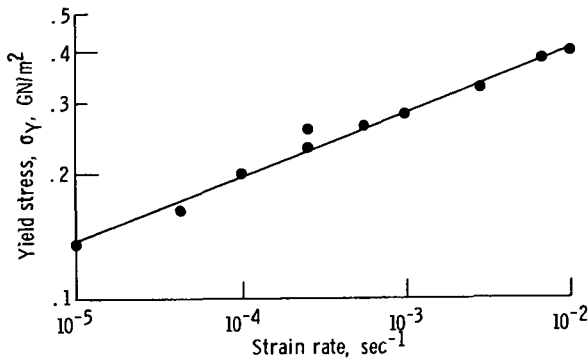


Figure 10. - Effect of strain rate on yield stress of tungsten at 525 K (0.14 T_m). (From ref. 22.)

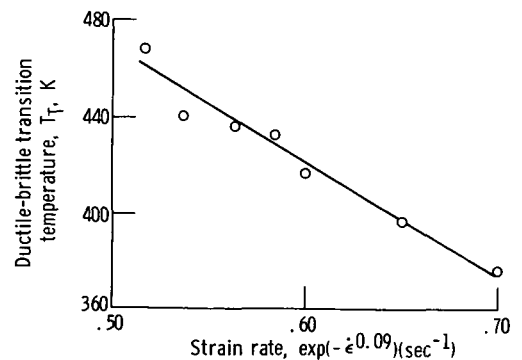


Figure 11. - Effect of strain rate on ductile-brittle transition temperature of tungsten. (From ref. 23.)

Raffo (ref. 5) has determined the strain rate sensitivity of tungsten over a range of temperatures. The strain rate sensitivity λ was calculated as

$$\lambda = \frac{(\Delta\sigma)_T}{\Delta \ln \dot{\epsilon}}$$

A plot of λ against T is shown in figure 12, where it should be noted that λ passes through a maximum at a temperature near 500 K, or near the DBTT for the arc-melted tungsten used in this study. The occurrence of a maximum in the strain rate sensitivity at an intermediate temperature is typical also of other bcc metals (ref. 24).

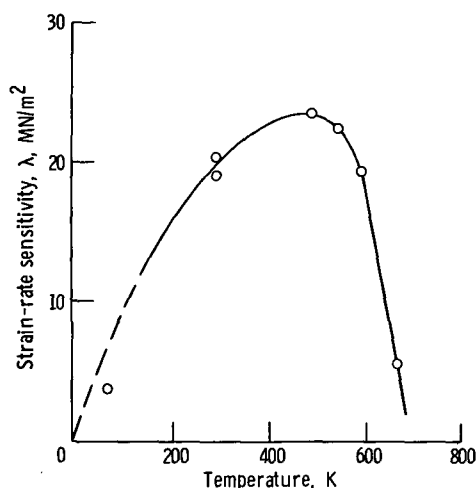


Figure 12. - Strain rate sensitivity of unalloyed, arc-melted tungsten. (From ref. 5.)

The dependence of the deformation behavior of tungsten on strain rate emphasizes the need for specified constant-strain-rate tests. The DBTT decreases with decreasing strain rate; therefore, testing at lower strain rates provides a means for determining the tensile properties of tungsten at lower temperatures.

Grain Size

The effect of grain size on the deformation behavior of tungsten has been reported on by a number of investigators (refs. 25 to 30). The DBTT has been described by several investigators to increase with an increase in grain size; other investigators, for example, Klopp and Witzke (ref. 30) and Thornley and Wronski (ref. 29), have noted

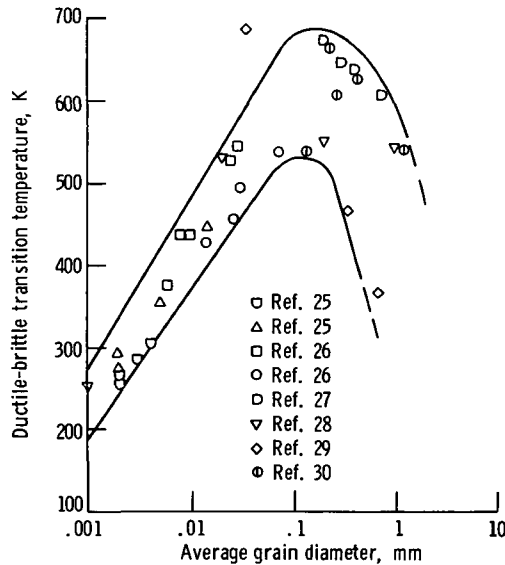


Figure 13. - Effect of grain size on the ductile-brittle transition temperature of tungsten.

a decrease in DBTT with increase in grain size at large grain sizes. Figure 13 summarizes the reported grain size dependency of DBTT for tungsten and shows that the DBTT reaches a maximum at an intermediate grain size.

Farrell, Schaffhauser, and Stiegler (ref. 28) reported little or no dependence of DBTT on grain size, but as can be seen in figure 13 their data lie within the knee of the curve. The large scatter in the data from the various investigators can be explained by the variation and distribution of impurities in the various lots of material used in the studies. Variation in grain size was normally achieved by annealing at various temperatures above the recrystallization temperature; and depending upon initial impurity content, cooling rate, and so forth, a wide variation in impurity distribution could result which, as shown by Koo (ref. 31), could overshadow the grain size effect.

In summary, the data suggest that for grain sizes less than approximately 0.1-millimeter diameter the DBTT increases with increasing grain size, while for larger grain sizes a decrease in DBTT is observed as grain size increases. A similar behavior has been reported for iron (ref. 32).

The effect of grain size on the yield stress of tungsten is not as well documented as the DBTT results. Koo (ref. 33) found that the lower yield stress of specimens tested at 873 K ($0.22 T_m$) obeyed a Petch relation with subgrain size. A similar relation was found for the data of Thornley and Wronski (ref. 29) and Klopp and Witzke (ref. 30) upon plotting the yield stress σ_Y at 500 K ($0.14 T_m$) against grain diameter as shown in figure 14. The data fit a relation of the form

$$\sigma_Y = \sigma_0 + k_Y d^{-1/2}$$

where σ_0 is equal to the yield stress of a single crystal, k_Y is a measure of the stress for propagation of yielding through a polycrystalline material (ref. 34), and d is the average grain diameter. Therefore, it is concluded that the yield stress data for tungsten at temperatures $< 0.2 T_m$ can be correlated with grain size by using a Petch relation.

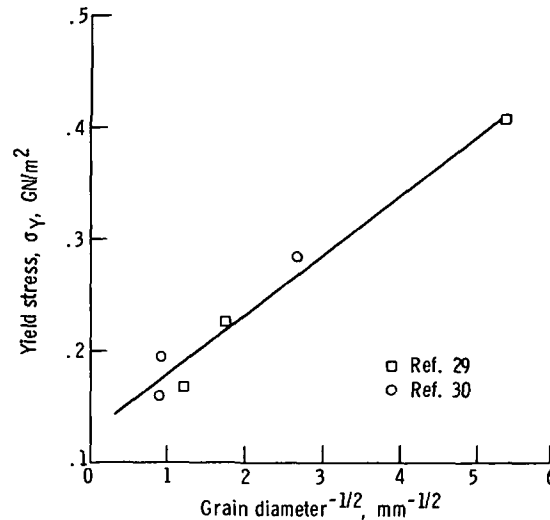


Figure 14. - Variation of yield stress with grain size at 500 K.

Interstitial Impurities

One of the primary factors believed to be responsible for the high DBTT of tungsten and the rapid increase in σ_Y with decreasing temperature is the presence of interstitial impurities. Analysis of wrought tungsten made by powder-metallurgy techniques typically shows high concentrations of interstitial impurities, primarily oxygen and carbon. Because of this, emphasis was placed on purification by arc melting, electron-beam melting, and electron-beam zone refining of single crystals. With the exception of single crystals, no dramatic decrease in DBTT resulted from the purification treatments. The results of Allen, Maykuth, and Jaffee (ref. 35) showed that polycrystalline tungsten made from high-purity single crystals had a DBTT only 55 K less than commercial powder-metallurgy tungsten with a much higher interstitial content.

Attempts by Sutherland and Klopp (ref. 36) to correlate DBTT with interstitial impurity content showed that oxygen and possibly hydrogen were detrimental to the DBTT of tungsten sheet produced by powder-metallurgy techniques.

The author (ref. 37) investigated the effects of oxygen and carbon on the DBTT and σ_Y of single-crystal and polycrystalline tungsten by adding controlled amounts of the interstitial impurities. Figure 15 illustrates the increase in DBTT of tungsten with varying amounts of oxygen or carbon. It should be noted that the interstitial impurities have only a minor effect on the DBTT of single-crystal material, while for polycrystalline tungsten a 200 to 300 K increase in DBTT resulted from the maximum concentration of impurities investigated. Oxygen appears to be more detrimental to the DBTT than does carbon at equivalent concentration levels.

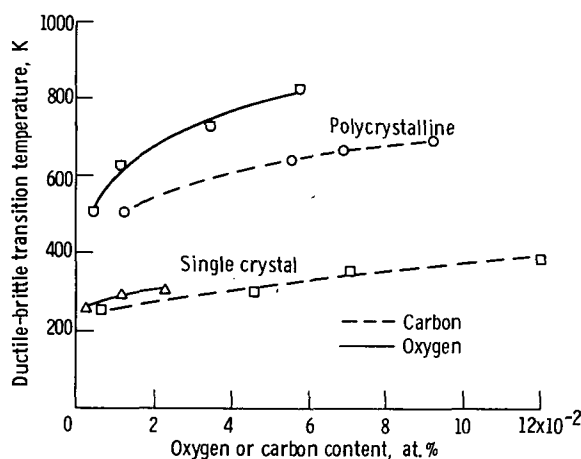


Figure 15. - Effects of oxygen and carbon on ductile-brittle transition temperature of single-crystal and polycrystalline tungsten. (From ref. 37.)

The variation of σ_Y with impurity content is shown in figure 16 where it should be noted that, in polycrystalline tungsten, oxygen lowers σ_Y , while carbon produces an increase in σ_Y . In single-crystal tungsten, σ_Y was independent of oxygen content, while increasing the carbon content of the zone-melted rods from 60 atom parts per million to 460 atom parts per million resulted in a twofold increase in σ_Y . Further additions of carbon up to 1200 atom parts per million failed to increase σ_Y further.

From these data two different mechanisms of embrittlement were postulated by the author (ref. 37). The embrittlement arising from oxygen additions is believed to be due to segregation of oxygen to grain boundaries, which provides an easy path for intergranular fracture by lowering the surface energy for fracture. Carbon embrittlement is believed to be primarily due to interactions between dislocations and carbide particles, which leads to embrittlement by increasing the yield stress and the unpinning stress.

A similar study was conducted by Savitskiy and Tsarev (ref. 38) on tungsten single

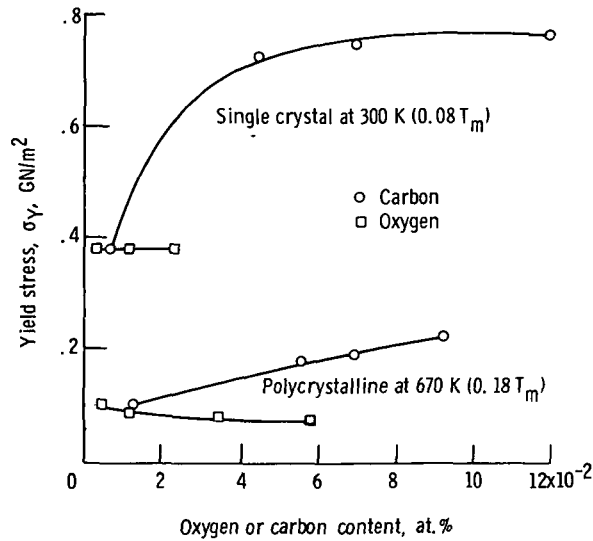


Figure 16. - Effects of oxygen and carbon on yield stress of single-crystal and polycrystalline tungsten. (From ref. 37.)

crystals which showed that carbon increased σ_Y by a factor of 2 and increased the DBTT, in agreement with the author. They were unable to add a significant amount of oxygen to tungsten, but did notice a slight decrease in σ_Y which was attributed to decarburization upon heating tungsten in the presence of oxygen.

The results of these two studies point out the importance of testing high-purity material in order to gain insight into the mechanisms controlling the mechanical behavior of tungsten at temperatures $< 0.2 T_m$.

It should be noted that the temperature dependence of the yield stress did not change significantly upon adding oxygen or carbon to single-crystal tungsten. Recent results by Oku and Galligan (ref. 39) have shown that one- and three-pass zone-melted tungsten have quite similar temperature dependencies from 300 to 77 K; but from 77 to 4.2 K the one-pass rods showed a much higher yield stress than did the three-pass rods, and the temperature dependence of the yield stress was higher for the one-pass rod. These results are shown in figure 17 compared with results of the author (ref. 37). Over the temperature range investigated, 420 to 4.2 K (0.1 to $0.001 T_m$), there is an approximate fivefold increase in σ_Y for tungsten of very high purity (three-pass rod).

These results suggest that the sharp temperature dependence of yield stress for tungsten is due to an intrinsic property rather than to the extrinsic properties discussed in this section. The following section reviews the effects of the intrinsic properties of tungsten on its deformation behavior.

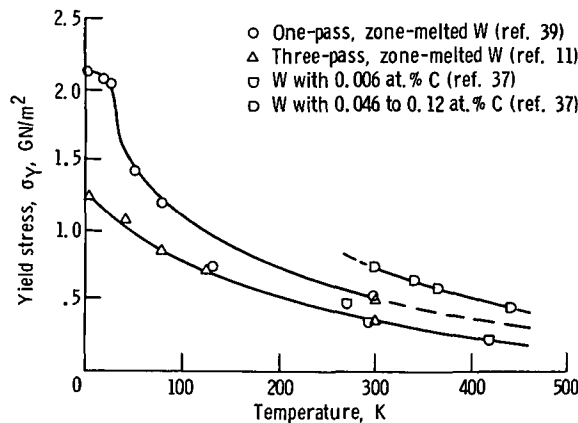


Figure 17. - Temperature dependence of yield stress for single-crystal tungsten of different purities.

INTRINSIC FACTORS

The body-centered cubic lattice of tungsten is the controlling parameter for such intrinsic factors as slip systems, twin systems, stacking fault energy, dislocation interactions, and so forth. In keeping with the purpose of this report, not all the investigations on slip of tungsten, for example, will be reviewed; but only those results that give insight to the problem of the DBTT or to the sharp temperature dependence of σ_Y at temperatures $< 0.2 T_m$. Obviously extrinsic factors discussed previously will be present in studies aimed at elucidating intrinsic factors such as slip or twin systems. In general, the extrinsic factors have been kept to a minimum by most investigators where this is possible. Studies of intrinsic factors have been performed on single-crystal specimens of relative high purity, tested at low strain rates, and with an electropolished surface.

Crystal Orientation

The effects of crystallographic orientation on the deformation behavior of tungsten single crystals has been the subject of much research over the past decade (refs. 39 to 46). Several interesting and unexpected features of the deformation behavior of tungsten have been reported by various investigators. The first of these was the effect of orientation (ref. 40) on the stress-strain curves as shown in figure 18, where it should be noted the proportional limit stress σ_P is highly orientation dependent. However, the values for σ_P apparently do not obey a critical resolved shear stress law (refs. 40 and 41).

It would be expected, for example, that σ_P should be the same for $[100]$ or $[110]$ oriented crystals since the Schmid factors for slip on particular $\{110\} \langle 111 \rangle$, $\{112\} \langle 111 \rangle$, or $\{123\} \langle 111 \rangle$ slip systems are essentially identical for both orientations. Garfinkle (ref. 43) has shown by strain gauge measurements where strains of 2×10^{-6} could be readily detected that the departure from linearity was indeed quite similar for the $[100]$ and $[110]$ orientations. His results are shown in the insert in figure 18 where values of σ_P of 0.035 and 0.045 giganewtons per square meter (5 and 6.5 ksi) were determined for $\langle 100 \rangle$ and $\langle 110 \rangle$ oriented crystals, respectively. These precise strain measurements indicate that the critical resolved shear stress criterion for slip initiation is applicable in tungsten crystals, at least for $[100]$ and $[110]$ orientations.

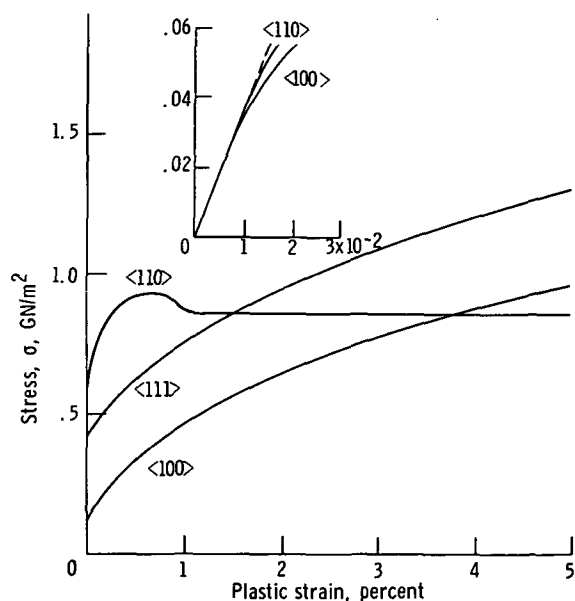


Figure 18. - Stress-strain curves for single-crystal tungsten at 300 K. (From refs. 40 and 43.)

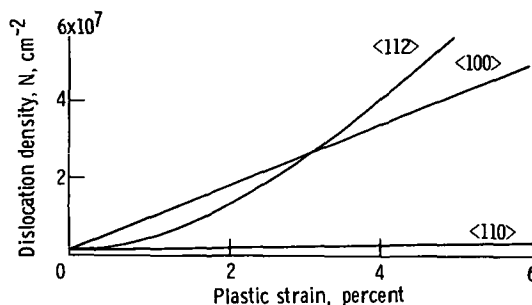


Figure 19. - Increase in dislocation density with plastic strain for single-crystal tungsten having various orientations. (From ref. 44.)

The macroscopic stress-strain curves for the various crystallographic orientations are still of interest since they indicate highly different rates of work hardening for different orientations and may give some insight into the mechanisms controlling the deformation of tungsten at $<0.2 T_m$.

The results of Argon and Maloof (ref. 44) help clarify the orientation dependence of plastic flow in tungsten. Figure 19 shows a plot of dislocation density N against strain for three orientations. Dislocation density was determined by the etch pit technique and by transmission microscopy. The extremely low rate of dislocation multiplication for $\langle 110 \rangle$ oriented crystals suggests that dislocations could glide large distances on parallel planes without intersecting other dislocations and leading to an increase in N . This

gives further insight to the low work hardening rate of $\langle 110 \rangle$ oriented crystals. The low density of dislocations and the large mean free path over which they can move would be expected to produce little work hardening.

The yielding phenomenon of the $\langle 110 \rangle$ oriented crystals was further investigated by prestraining and aging experiments (ref. 44). Results indicated that the characteristic return of the yield point for dislocation-interstitial reactions was not present in the single-crystal tungsten specimens, thus suggesting that the discontinuous yield phenomenon of $\langle 110 \rangle$ crystals is an inherent property.

The effect of temperature on σ_Y for single-crystal tungsten (refs. 39, 42, and 44) having high symmetry orientations is shown in figure 20. A sharp temperature dependency of σ_Y is noted for all three orientations and appears to be a characteristic of tungsten as well as other bcc metals.

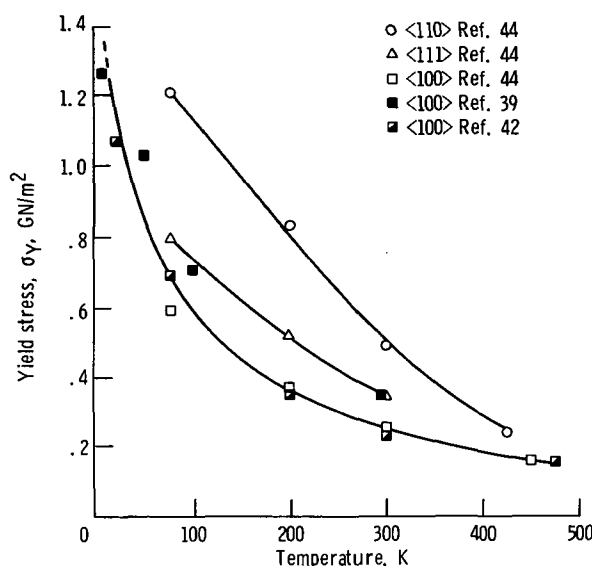


Figure 20. - Effect of temperature on yield stress of tungsten single crystals having various orientations.

A second anomaly reported by various investigators is the absence of detectable surface slip lines until deformations as high as 5 to 15 percent strain (refs. 40, 41, 42, and 44). However, more recently Kaun, Luft, Richter, and Schulze (ref. 46), using specimens with specially prepared surfaces, have shown that slip lines are observable on tungsten single crystals after strains of only 0.1 percent. After strains of 0.3 percent, additional slip planes other than the primary slip planes were observable. Previous attempts to correlate the critical resolved shear stress with slip lines observable after much larger deformations undoubtedly were involved with secondary slip systems

which contributed to apparent failure of a critical resolved shear stress law being obeyed. These results, along with the microstrain results (ref. 43), indicate that deformation of tungsten follows predictable behavior at extremely small strains.

It should be noted that the ductility of tungsten is greatly increased when tested in single-crystal form. Appreciable ductility was observed for $\langle 100 \rangle$ crystals at 20 K ($0.005 T_m$; ref. 42) and even at 4.2 K ($0.001 T_m$; ref. 39), demonstrating that tungsten is not inherently brittle in the absence of grain boundaries. Necking was observed at 20 K (ref. 42) when the specimen surface was free of any scratches resulting from handling. Premature failure occurred when scratches were present, indicating the extreme notch sensitivity of tungsten. Fracture is normally characterized by a ductile chisel-type fracture or by some necking followed by cleavage on $\{001\}$ planes.

In summary, results show that crystal orientation has a primary role in the deformation of single-crystal tungsten at low temperatures. All orientations investigated exhibit a sharp temperature dependence of σ_Y below about $0.1 T_m$. However, the sharp DBTT which characterizes polycrystalline tungsten is not evident in single crystals if extrinsic factors such as surface scratches are kept to a minimum. Appreciable ductility at 4.2 K ($0.001 T_m$) suggests that tungsten is not inherently brittle.

Stacking Fault Energy and Twinning Stress

The high stacking fault energy of tungsten precludes the importance of stacking faults playing a direct role in the deformation behavior of tungsten. Isolated cases of stacking faults being observed in tungsten have been reported by Nakayama, Weissmann, and Amura (ref. 47) and by Demny (ref. 48). Stacking faults were produced by heating tungsten above 2275 K and quenching or by slightly deforming above 2775 K and quenching (ref. 47). In the second instance stacking faults were formed by heating a thin foil of tungsten directly in the electron microscope while the foil was held rigidly (ref. 48). Under normal loading conditions, stacking faults have not been observed in tungsten, thus indicating that separation of dislocations does not occur in tungsten, at least to a detectable width.

It has been shown by Venables (ref. 49) that the twinning stress for face-centered cubic (fcc) metals is proportional to the stacking fault energy. However, there are conflicting evidences for the occurrence of twinning as a primary mode of deformation in tungsten (bcc). Wolff (ref. 50) has reported room-temperature twinning in tungsten on $\{112\}$ planes associated with fracture after considerable deformation by slip. Most of the data of this investigation were interpreted to indicate that twinning led to fracture, while the reverse was true in isolated cases. Koo (ref. 51) observed that increased purity (increase in number of zone-melting passes) promoted twinning at temperatures

ranging from 180 to 95 K, but found no twinning at 77 K. Twinning occurred in the macroscopic elastic region of deformation, in contradiction to the previous results of Wolff.

In a more recent study, Beardmore and Hull (ref. 42) found no evidence of twinning initiating fracture; and their observations indicated that twins were caused by cracks. Metallographic examination of $[100]$ crystals (most favorable orientation for twinning) after various stages of deformation at 20 to 465 K failed to reveal any evidence of twinning.

The reasons for the various inconsistencies concerning twinning in tungsten are not completely understood. It is known that twinning in bcc metals is more likely to occur at low temperatures, high strain rates, and in high-purity material. Comparable strain rates were used in the previous studies and four or five zone-melting passes were used in preparation of the single crystals.

It is concluded that stacking faults of observable widths are unimportant in the deformation of tungsten and that twins under some conditions can play a role in the deformation of tungsten.

Dislocation Mobility

Two recent investigations by the author (refs. 52 and 53) were concerned with the dislocation structures in tungsten after deformation at temperatures $< 0.2 T_m$. The first of these studies (ref. 52) determined the dislocation distribution after various strains at room temperature ($0.08 T_m$) in polycrystalline tungsten. Transmission electron microscopy (TEM) revealed an increase in dislocation density with strain for plastic strains up to 5 percent, as shown in figure 21. Dislocation structures corre-

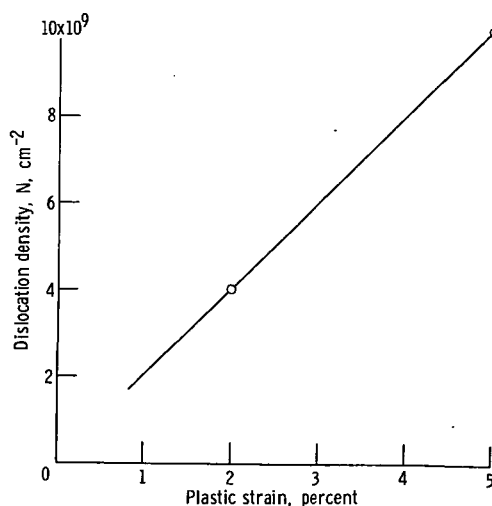
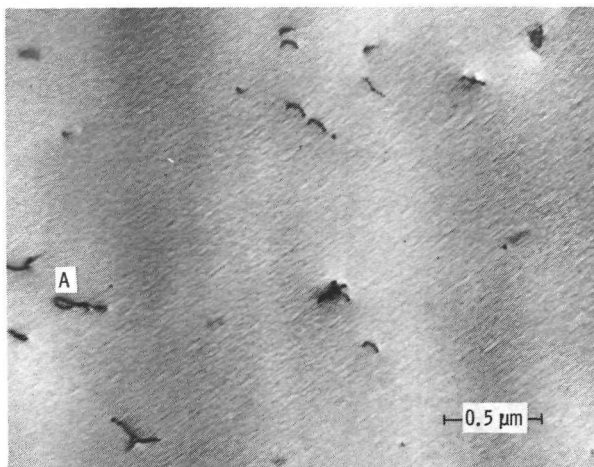
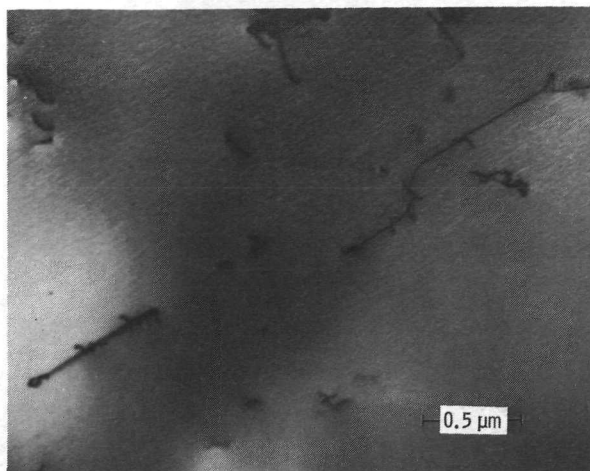


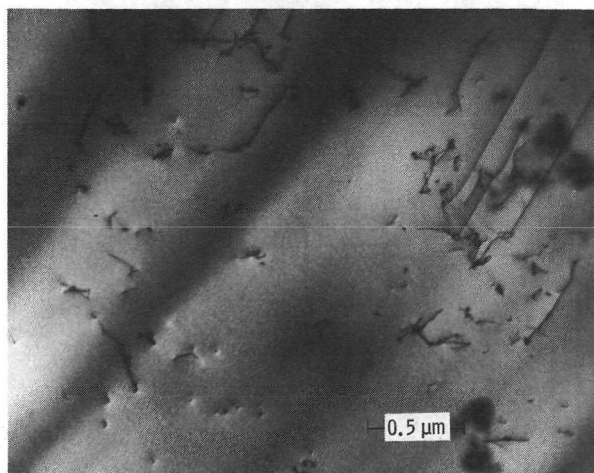
Figure 21. - Variation of dislocation density with strain for polycrystalline tungsten. (From ref. 52.)



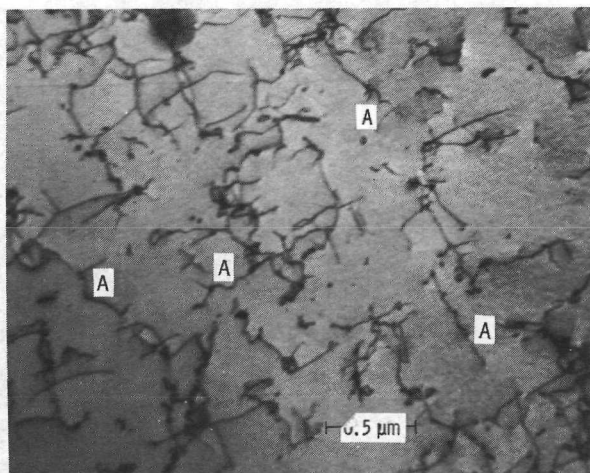
(a) Strain, 0.05 percent.



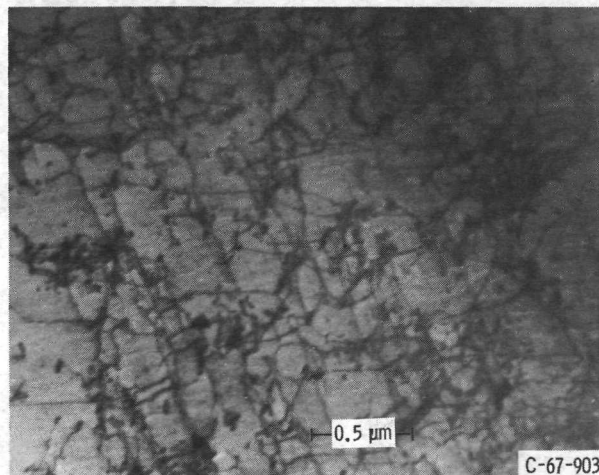
(b) Strain, 0.1 percent.



(c) Strain, 0.5 percent.

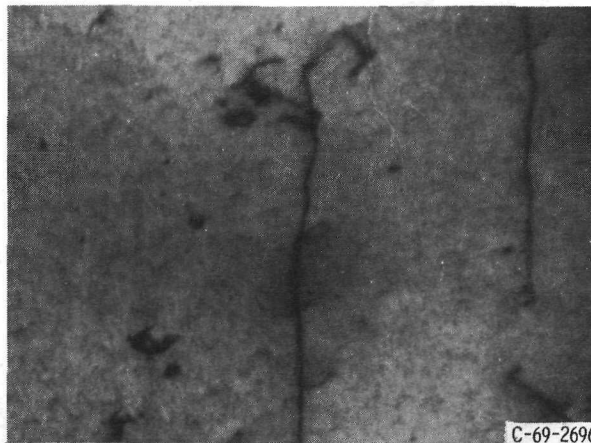


(d) Strain, 2 percent.

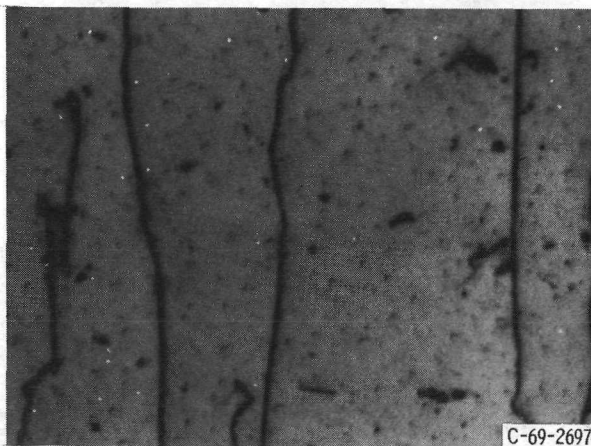


(e) Strain, 5 percent.

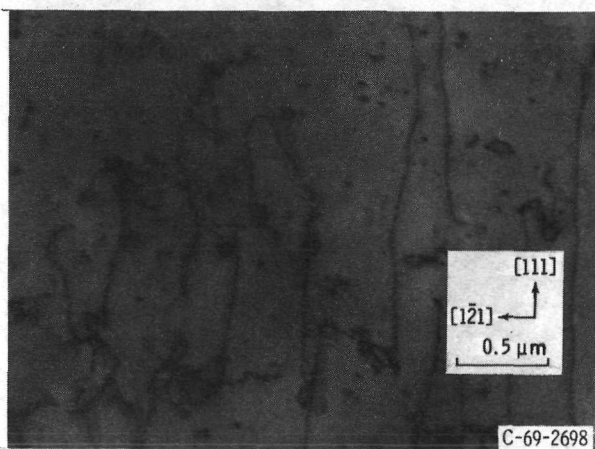
Figure 22. - Dislocation structure in unalloyed tungsten after testing in compression at room temperature.



(a) Strain, 1 percent.



(b) Strain, 2 percent.

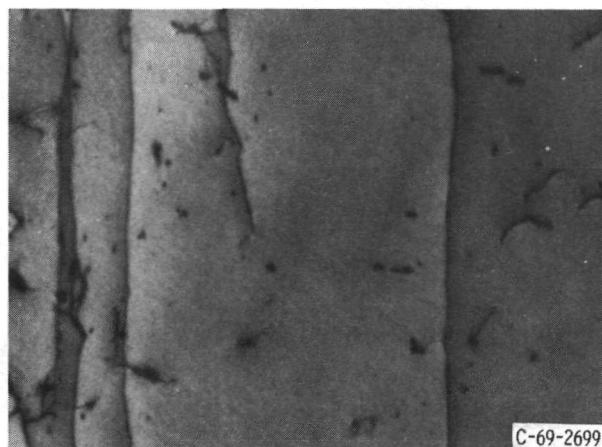


(c) Strain, 5 percent.

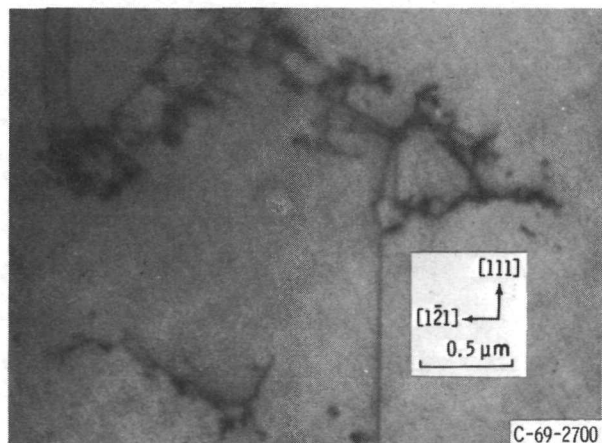
Figure 23. - Dislocation structures in unalloyed tungsten single crystals after testing in compression at 300 K ($0.08 T_m$).

sponding to various amounts of strain are shown in figure 22. Of particular interest was the presence of long screw dislocations after slight amounts of strain; that is, figures 22(b) and (c) after strains of 0.1 and 0.5 percent, respectively. With further strain dislocation, movement on more than one slip plane became evident, as noted in figures 22(d) and (e) for strains of 2 and 5 percent. Tangling of dislocations resulted, but cell formation was not evident even after 5 percent strain. Individual dislocations remained straight over large distances, with frequent cusps along their length such as at "A" in figure 22(d).

In a second study on single-crystal tungsten oriented for $(\bar{1}01)[111]$ slip, TEM revealed long screw dislocations in the $(\bar{1}01)$ plane lying parallel to the primary slip direction as shown in figures 23(a) to (c) after various amounts of strain at 300 K ($0.08 T_m$).



(a) Temperature, 150 K ($0.04 T_m$).



(b) Temperature, 590 K ($0.16 T_m$).

Figure 24. - Effect of temperature on dislocation substructure in single-crystal tungsten tested in compression to 2 percent strain.

Only after 5 percent strain is there evidence of dislocation tangling and trapping of edge dislocations (fig. 23(c)).

Effects of temperature on dislocation distribution and mobility are shown in figure 24. Specimens deformed at 150 K ($0.04 T_m$) were characterized by long, straight screw dislocations lying parallel to the primary slip direction (fig. 24(a)). In contrast, deformation at 590 K ($0.16 T_m$) resulted in a structure characterized by edge dislocations lying parallel to the $[\bar{1}21]$ direction (fig. 24(b)).

Based on the dislocation distributions observed in these two studies, it is concluded that, at temperatures $<0.1 T_m$, edge dislocation mobility is much greater than is screw dislocation mobility. Consequently, edge dislocations can move through the crystal, leaving behind the long screw segments. Another indication of the forces inhibiting screw dislocation mobility is the straightness of the screw dislocations at temperatures $<0.1 T_m$. At temperatures $>0.1 T_m$, edge and screw mobility become equal and both types of dislocations are observed (i.e., fig. 24(b) after deformation at $0.16 T_m$). The decrease in screw dislocation mobility as test temperature decreases can be correlated with the temperature dependence of σ_Y for tungsten. Higher stresses are needed at lower temperatures to produce dislocation movement after edge dislocations have moved out of the crystal.

CONTROLLING MECHANISMS

There are three predominant models that have been proposed to explain the temperature dependency of the yield stress of bcc metals at temperatures $<0.2 T_m$. The first postulates that an extrinsic factor, interstitial impurities, controls dislocation movement and ductility (ref. 54). The second model (ref. 55) hypothesizes that an intrinsic factor, the inherent lattice resistance (Peierls mechanism), is controlling; while the third model (ref. 56) proposes that deformation is dependent upon recombination of mildly dissociated screw dislocations. Because of the high stacking fault energy of tungsten and the lack of mobility of screw dislocations in tungsten at low temperatures and low strains, it does not appear that dissociation of screw dislocations can play an important role in the deformation of tungsten. Therefore, the third model, proposed by Escaig (ref. 56), will not be considered further in this review.

Recent results on Group V metals (tantalum, niobium, and their alloys (refs. 57 and 58)) have given considerable support to an extrinsic factor, interstitial impurities, as the primary factor responsible for the sharp temperature dependency of σ_Y in bcc metals. In contrast, investigations of the yield behavior of tungsten (ref. 44), the dislocation mobility in tungsten (refs. 52 and 53), the alloying effects on low-temperature deformation of tungsten (refs. 5, 52, and 53), and the micro-yielding of tungsten (ref.

59) all lead to the conclusion that an intrinsic factor, a Peierls mechanism, controls low-temperature deformation of tungsten. Although it is tempting to propose that the deformation behavior of Group V metals should be applicable to Group VI metals, Chen (ref. 60) in a recent review of the physical properties of the two transition metal groups has proposed a subdivision of the bcc metals based on differences in the electronic structure and nuclear composition between Group V (vanadium, niobium, and tantalum) and Group VI (chromium, molybdenum, and tungsten). Differences in mechanical behavior and in diffusion of oxygen in the two groups of metals were also cited as lending support to this type of subdivision. It is concluded by Chen that systematic changes in many physical properties upon going from one group to the other are manifestations of the subdivision and that mechanical properties may be expected to show a marked difference in behavior.

Based on experimental evidence cited previously for tungsten, it is concluded that an intrinsic lattice resistance to dislocation motion, a Peierls mechanism, controls the deformation behavior of tungsten at low temperatures. This mechanism can explain the presence of long screw dislocations observed by the author (ref. 53) in single-crystal tungsten after slight amounts of deformation. Arsenault, Crowe, and Carnahan (ref. 61) have calculated that the Peierls stress of a screw dislocation on a (110) slip plane is approximately 10^3 larger than that for an edge dislocation. Hence, the edge dislocations can move out of the specimen, leaving behind long segments of screw dislocations. The straightness of the screw dislocations in specimens deformed at 150 K ($0.04 T_m$) is further evidence of a high stress acting upon them. Since thermal fluctuations can assist screw dislocations in overcoming the Peierls stress, increasing temperature will increase screw dislocation mobility until edge and screw mobility become more equal; and the structure will then be characterized by both edge and screw dislocations.

The temperature dependence of the yield stress arises because of the lack of mobile screw dislocations due to the high Peierls stress acting upon screw dislocations especially at temperatures $< 0.1 T_m$.

It has been suggested by Crutchley and Reid (ref. 62) that the brittleness of the bcc metals is an inherent property related to the nature of the atomic bonding which is manifested in the elastic constants. They consider low values of the ratio of bulk modulus K to shear modulus μ on a active slip system as indicative of inherent brittleness. The Group V metals vanadium, niobium, and tantalum have K/μ values ranging from 3.12 to 4.03, while the Group VI metals chromium, molybdenum, and tantalum have K/μ values ranging from 1.22 to 2.02 (ref. 62). It is thus concluded that Group VI metals will be extremely notch sensitive and will behave in a manner quite differently than Group V metals. Even though ductility is observed in tungsten at $0.001 T_m$, it is possible that the nature of the atomic bonding makes tungsten more susceptible to embrittlement. Hence, the high DBTT of tungsten can be thought of as being controlled by intrinsic properties acting indirectly and extrinsic properties playing a direct role.

ALLOYING

The most attractive alloy addition to tungsten for improving the low-temperature ductility is rhenium. This beneficial effect occurs at low concentrations, up to approximately 5-atom-percent rhenium and also at higher concentrations near the maximum solubility of rhenium in tungsten, ~ 25 -atom-percent rhenium. Dilute rhenium additions have been shown to reduce the ductile-brittle transition temperature (ref. 63), to reduce the temperature dependence of the yield stress (ref. 5), and to increase dislocation mobility and multiplication rates in tungsten (refs. 52 and 53). These phenomena are characteristics of alloy softening (ref. 64).

A lowering of the Peierls stress has been postulated to explain the enhanced mechanical properties of dilute tungsten-rhenium alloys. Concentrated rhenium additions, near 25 atom percent, also lower the DBTT; and it is postulated (ref. 60) that such gross alloying may have a favorable effect on the K/μ ratio, which may improve the ductility of tungsten. In both cases rhenium is important because of its effect on the intrinsic properties of tungsten.

CONCLUDING REMARKS

This report has attempted to summarize some of the research studies that have helped to characterize the low-temperature deformation behavior of tungsten. Some of the early anomalous behavior reported for tungsten has been clarified with more sensitive and exact studies. For example, slip lines are observed after less than 1 percent strain; microstrain measurements suggest tungsten obeys a Schmid law for single-crystal deformation; there is a critical grain size below which the ductile-brittle transition temperature (DBTT) decreases with decreasing grain size; and the Petch relation between yield stress σ_Y and grain size is obeyed.

It is concluded that the sharp temperature dependency of σ_Y and the relatively high DBTT of tungsten are manifestations of intrinsic properties. For practical applications of tungsten, extrinsic factors discussed in this report, such as strain rate and surface defects, will also add on to the intrinsic properties and further increase the DBTT.

Alloying should be aimed at altering the intrinsic properties of tungsten. It appears that electron concentration plays a major role in the mechanical behavior of tungsten when it is alloyed with other transition metals. For example, the effects of sixth period elements, hafnium and platinum, on the hardness of molybdenum (a Group VI metal along with tungsten) can best be correlated with electron concentration, as discussed in unpublished work by the author, rather than with atomic size misfit or modulus differences which have been successfully applied to hardening of face-centered cubic metals.

A clearer understanding of the role of electron concentration and bonding of the transition metals and their relation to mechanical behavior should provide challenging research for those involved with the deformation of tungsten and other transition metals.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 15, 1971,
114-03.

REFERENCES

1. Promisel, N. E.: Why Refractory Metals? The Science and Technology of Tungsten, Tantalum, Molybdenum, Niobium and Their Alloys. AGARDograph 82. N. E. Promisel, ed., Pergamon Press, 1964, pp. 3-13.
2. Sherwood, P. J.: Applications of Some Refractory Metals in Space Technology. Brit. Interplanetary Soc. J., vol. 22, no. 6, Dec. 1969, pp. 385-392.
3. Bechtold, J. H.; and Shewmon, P. G.: Flow and Fracture Characteristics of Annealed Tungsten. Trans. ASM, vol. 46, 1954, pp. 397-408.
4. Wronski, A.; and Fourdeux, A.: Slip-Induced Cleavage in Polycrystalline Tungsten. J. Less-Common Metals, vol. 6, 1964, pp. 413-429.
5. Raffo, P. L.: Yielding and Fracture in Tungsten and Tungsten-Rhenium Alloys. J. Less-Common Metals, vol. 17, Feb. 1969, pp. 133-149.
6. Low, John R., Jr.: Microstructural Aspects of Fracture. Fracture of Solids. Vol. 20. D. C. Drucker and J. J. Gilman, eds., Interscience Publishers, 1963, pp. 197-236.
7. Wronski, A. S.; Chilton, A. C.; and Capron, E. M.: The Ductile-Brittle Transition in Polycrystalline Molybdenum. Acta Met., vol. 17, no. 6, June 1969, pp. 751-755.
8. Hull, D.; Beardmore, P.; and Valintine, A. P.: Crack Propagation in Single Crystals of Tungsten. Phil. Mag., vol. 12, no. 119, Nov. 1965, pp. 1021-1041.
9. Valintine, Anne P.; and Hull, D.: Effect of Temperature on the Brittle Fracture of Polycrystalline Tungsten. J. Less-Common Metals, vol. 17, Apr. 1969, pp. 353-361.
10. Bridgman, Percy W.: Studies in Large Plastic Flow and Fracture with Special Emphasis on the Effects of Hydrostatic Pressure. McGraw-Hill Book Co., Inc., 1952.

11. Das, G.; and Radcliffe, S. V.: Effects of Hydrostatic Pressure on the Mechanical Behavior of Tungsten. *Trans. Japan Inst. Metals*, vol. 9, Supplement, 1968, pp. 334-342.
12. Wronski, A. S.; and Chilton, A. C.: The Effects of Temperature and Pressurization on the Tensile and Compressive Properties of Polycrystalline Cast Tungsten. *Scripta Met.*, vol. 3, no. 6, June 1969, pp. 395-400.
13. Mellor, H. G.; and Wronski, A. S.: The Effects of Precompression and Pressurization on the Ductile-Brittle Transition of Polycrystalline Cast Chromium, Molybdenum and Tungsten. University of Bradford Materials Science Research Final Report, Univ. Bradford, England, Feb. 1970.
14. Das, G.; and Radcliffe, S. V.: Pressure-Induced Development of Dislocations at Elastic Discontinuities. *Phil. Mag.*, vol. 20, no. 165, Sept. 1969, pp. 589-609.
15. Sedlatschek, K.; and Thomas, D. A.: The Effect of Surface Treatment on the Mechanical Properties of Tungsten. *Powder Met. Bull.*, vol. 8, no. 1/2, June 1957, pp. 35-40.
16. Stephens, Joseph R.: An Exploratory Investigation of Some Factors Influencing the Room-Temperature Ductility of Tungsten. NASA TN D-304, 1960.
17. Stephens, Joseph R.: Effect of Surface Condition on Ductile-To-Brittle Transition Temperature of Tungsten. NASA TN D-676, 1961.
18. Stephens, J. R.: Effect of Surface Condition on the Ductility of Tungsten. *High Temperature Materials II*. G. M. Ault, W. F. Barclay and H. P. Munger, eds., Interscience Publishers, 1963, pp. 125-137.
19. Stephens, Joseph R.: Effect of Oxygen on Mechanical Properties of Tungsten. NASA TN D-1581, 1963.
20. Berghezan, A.: Role of the Surface on the Strength, Ductility and Embrittlement of Refractory Metals. Paper presented at the Metallurgical Society Meeting, AIME, Detroit, Mich., Oct. 23-26, 1961.
21. Steigerwald, E. A.; and Guarnieri, G. J.: Influence of Surface Oxidation on the Brittle-to-Ductile Transition of Tungsten. *Trans. ASM*, vol. 55, 1962, pp. 307-318.
22. Bechtold, James H.: Strain Rate Effects in Tungsten. *J. Metals*, vol. 8, no. 2, Feb. 1956, pp. 142-146.
23. Chilton, A. C.; and Wronski, A. S.: The Effects of Strain Rate and Pressurization on the Ductile-Brittle Transition Temperature of Polycrystalline Sintered Tungsten. *J. Less-Common Metals*, vol. 17, Apr. 1969, pp. 447-450.

24. Conrad, H.: The Cryogenic Properties of Metals. High-Strength Materials. V. F. Zackay, ed., John Wiley & Sons, Inc., 1965, pp. 436-509.
25. Seigle, L. L.; and Dickinson, C. D.: Effect of Mechanical and Structural Variables on the Ductile-Brittle Transition in Refractory Metals. Refractory Metals and Alloys II. I. Perlmutter and M. Semchyshen, eds., Interscience Publ., 1963, pp. 65-116.
26. Campbell, R. W.; and Dickinson, C. D.: Effect of Melting Variables on Purity and Properties of Tungsten. High Temperature Materials II. G. M. Ault, W. F. Barclay, and H. P. Munger, eds., Interscience Publ., 1961, pp. 655-668.
27. Gilbert, A.: A Fractographic Study of Tungsten and Dilute Tungsten-Rhenium Alloys. J. Less-Common Metals, vol. 10, 1966, pp. 328-343.
28. Farrell, K.; Schaffhauser, A. C.; and Stiegler, J. O.: Recrystallization, Grain Growth and the Ductile-Brittle Transition In Tungsten Sheet. J. Less-Common Metals, vol. 13, 1967, pp. 141-155.
29. Thornley, J. C.; and Wronski, A. S.: The Effects of Grain Size and Annealing Temperature on the Mechanical Properties of Cast Tungsten. Materials Science Research Final Report, Univ. Bradford, England, 1970.
30. Klopp, William D.; and Witzke, Walter R.: Mechanical Properties and Recrystallization Behavior of Electron-Beam-Melted Tungsten Compared with Arc-Melted Tungsten. NASA TN D-3232, 1966.
31. Koo, Ronald C.: Observations on the Ductility of Polycrystalline Tungsten as Affected by Annealing. Trans. AIME, vol. 227, no. 1, Feb. 1963, pp. 280-282.
32. Tahmoush, F. G.; Abrahamson, E. P., II; and Grant, N. J.: The Effect of Grain Size on the Brittle-Ductile Transition Temperature of Pure Iron and Some Dilute Iron-Tungsten Alloys. Trans. AIME, vol. 227, no. 2, Apr. 1963, pp. 505-509.
33. Koo, R. C.: Recovery in Cold-Worked Tungsten. J. Less-Common Metals, vol. 3, 1961, pp. 412-428.
34. McLean, D.: Mechanical Properties of Metals. John Wiley & Sons, Inc., 1962, pp. 199-200.
35. Allen, B. C.; Maykuth, D. T.; and Jaffee, R. I.: The Effects of Impurities on the Properties of Tungsten. Battelle Memorial Inst., (AFSWC-TR-60-6), Dec. 15, 1959.
36. Sutherland, E. C.; and Klopp, William D.: Observations of Properties of Sintered Wrought Tungsten Sheet at Very High Temperatures. NASA TN D-1310, 1963.

37. Stephens, Joseph R.: Effects of Interstitial Impurities on the Low-Temperature Tensile Properties of Tungsten. NASA TN D-2287, 1964.
38. Savitskiy, Ye. M.; and Tsarev, G. L.: Investigations of Effect of Interstitial Impurities on the Structure and Properties of Tungsten Single Crystals. NASA TT F-10157, 1966.
39. Oku, T.; and Galligan, J. M.: Plastic Deformation of Zone-Refined Tungsten Between 4.2 and 300 K. Rep. JAERI-Memo-4124, Japan Atomic Energy Research Inst., Aug. 1970.
40. Rose, R. M.; Ferriss, D. P.; and Wulff, J.: Yielding and Plastic Flow in Single Crystals of Tungsten. Trans. AIME, vol. 224, no. 5, Oct. 1962, pp. 981-990.
41. Garlick, R. G.; and Probst, H. B.: Investigation of Room-Temperature Slip in Zone-Melted Tungsten Single Crystals. Trans. AIME, vol. 230, no. 5, Aug. 1964, pp. 1120-1125.
42. Beardmore, P.; and Hull, D.: Deformation and Fracture of Tungsten Single Crystals. J. Less-Common Metals, vol. 9, 1965, pp. 168-180.
43. Garfinkle, M.: Proportional-Limit Stress of Tungsten Single Crystals. Trans. AIME, vol. 236, no. 9, Sept. 1966, pp. 1373-1374.
44. Argon, A. S.; and Maloof, S. R.: Plastic Deformation of Tungsten Single Crystals at Low Temperatures. Acta Met., vol. 14, no. 11, Nov. 1966, pp. 1449-1462.
45. Hull, D.; Byron, J. F.; and Noble, F. W.: Orientation Dependence of Yield In Body-Centered Cubic Metals. Can. J. Phys., vol. 45, no. 2, pt. 3, Feb. 1967, pp. 1091-1099.
46. Kaun, L.; Luft, A.; Richter, J.; and Schulze, D.: Slip Line Pattern and Active Slip Systems of Tungsten and Molybdenum Single Crystals Weakly Deformed in Tension at Room Temperature. Phys. Stat. Sol., vol. 26, 1968, pp. 485-499.
47. Nakayama, Y.; Weissmann, S.; and Imura, T.: Substructure and Dislocation Networks in Tungsten. Direct Observation of Imperfections in Crystals. J. B. Newkirk and J. H. Wernick, eds., Interscience Publ., 1962, pp. 573-592.
48. Demny, J.: Stacking Faults in Tungsten. Phys. Stat. Sol., vol. 22, 1967, pp. K1-K2.
49. Venables, J. A.: Deformation Twinning in FCC Metals. Deformation Twinning. R. E. Reed-Hill, J. P. Hirth, and H. C. Rogers, eds., Gordon and Breach Science Publ., 1964, pp. 77-116.
50. Wolff, Ursula E.: Twinning and Fracture in Tungsten Single Crystals at Room Temperature. Trans. AIME, vol. 224, no. 2, Apr. 1962, pp. 327-333.

51. Koo, R. C.: Effect of Purity on the Tensile Properties of Tungsten Single Crystals from -196°C to 29°C . *Acta Met.*, vol. 11, no. 9, Sept. 1963, pp. 1083-1095.
52. Stephens, Joseph R.: Dislocation Structures in Slightly Strained Tungsten, Tungsten-Rhenium, and Tungsten-Tantalum Alloys. *Trans. AIME*, vol. 242, no. 4, Apr. 1968, pp. 634-640.
53. Stephens, Joseph R.: Dislocation Structures in Single-Crystal Tungsten and Tungsten Alloys. *Metallurg. Trans.*, vol. 1, no. 5, May 1970, pp. 1293-1301.
54. Fleisher, R. L.: The Flow Stress of Body-Centered Cubic Metals: Inherent Lattice Hardening or Solution Hardening? *Acta Met.*, vol. 15, no. 9, Sept. 1967, pp. 1513-1519.
55. Conrad, H.: Yielding and Flow of the BCC Metals at Low Temperatures. The Relation Between the Structure and Mechanical Properties of Metals. Her Majesty's Stationery Office, 1963, pp. 475-516.
56. Escaig, B.: Origin of the Elastic Limit of Body-Centered Cubic Metals at Low Temperature. *J. Physique*, vol. 28, no. 2, Feb. 1967, pp. 171-186.
57. Smialek, R. L.; Webb, G. L.; and Mitchell, T. E.: Solid Solution Softening in BCC Metal Alloys. *Scripta Met.*, vol. 4, no. 1, Jan. 1970, pp. 33-38.
58. Ravi, K. V.; and Gibala, R.: The Strength of Niobium-Oxygen Solid Solutions. *Acta Met.*, vol. 18, no. 6, June 1970, pp. 623-634.
59. Bilello, John C.: Temperature Dependence of Micro-Yielding and the Transition to Macro-Strain for Tungsten. *Phil. Mag.*, vol. 19, Mar. 1969, pp. 583-598.
60. Chen, C. W.: Subdivision of the B.C.C. Transition Metals. *Phys. Stat. Sol.*, vol. 40, 1970, pp. 717-724.
61. Arsenault, R. J.; Crowe, C. R.; and Carnahan, R. D.: Dynamic Microplasticity of BCC Metals and Solid Solutions. EMG Rep. No. XXIII, Univ. Maryland, 1970.
62. Crutchley, D. E.; and Reid, C. N.: Mechanical Properties of Chromium Single Crystals. *High Temperature Materials*. F. Benesovsky, ed., Metallwerk Plansee Ag., 1969, pp. 57-66.
63. Klopp, William D.; Witzke, Walter R.; and Raffo, Peter L.: Mechanical Properties of Dilute Tungsten-Rhenium Alloys. NASA TN D-3483, 1966.
64. Stephens, J. R.; and Witzke, W. R.: Alloy Softening in Group VIA Metals Alloyed with Rhenium. *J. Less-Common Metals*, vol. 23, Apr. 1971, pp. 325-342.



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